Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

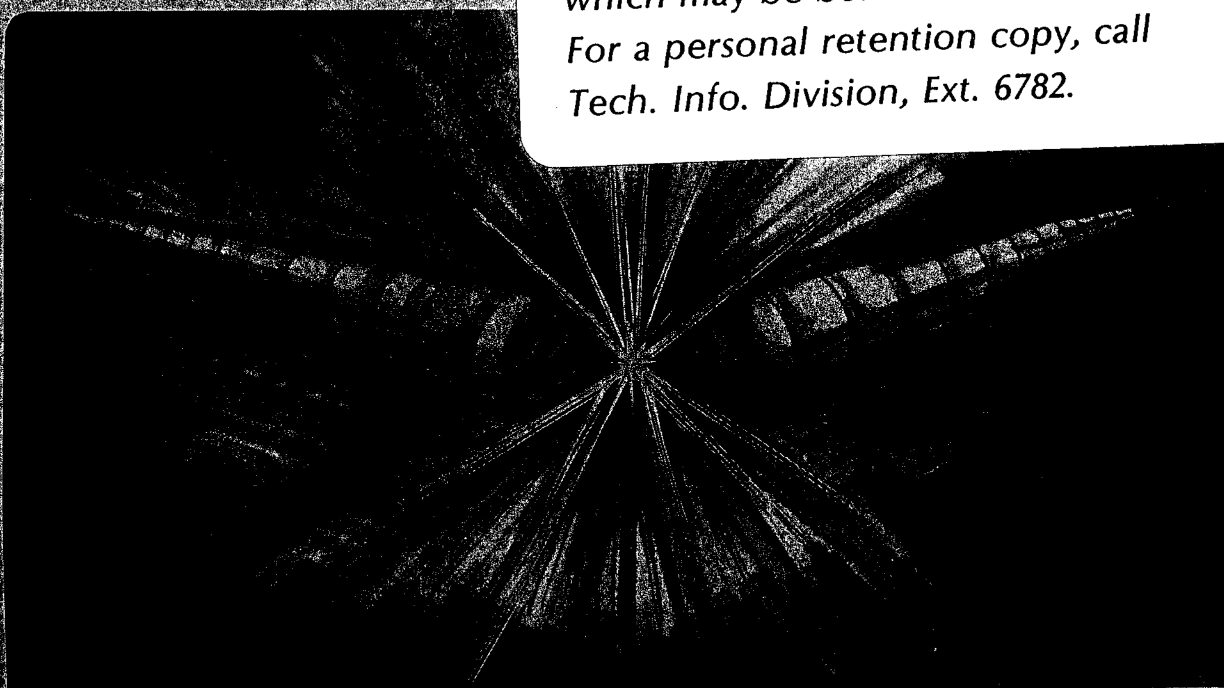
Accelerator & Fusion Research Division

Presented at the 5th International Conference on High-Power Particle Beams, San Francisco, CA, September 12-14, 1983

POWER-AMPLIFICATION OF A HEAVY-ION BEAM IN AN INDUCTION LINAC

A. Faltens and D. Keefe

September 1983



Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

LBL-16639

POWER-AMPLIFICATION OF A HEAVY-ION BEAM IN AN INDUCTION LINAC*

A. Faltens and D. Keefe

September 1983

Accelerator and Fusion Research Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

*This work was supported by the Assistant Secretary for Defense Programs, Office of Inertial Fusion, Laser Fusion Division, U.S. Department of Energy, under Contract No. DE-AC03-76SF00098.

POWER-AMPLIFICATION OF A HEAVY-ION BEAM IN AN INDUCTION LINAC

A. Faltens and D. Keefe
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

Abstract

In contrast to an rf linac - a constant-current device in which the beam power is increased solely by the addition of kinetic energy, qV, - the induction linac (I.L.) can amplify the beam power at a much more rapid rate. Proper programming of the switching of the modules and the shape of their voltage waveforms, in the early stages of acceleration, can result in a beam current that rises at a rate between $V^{1/2}$ *and V and, consequently, a beam power that varies in the range* $V^{3/2}$ *to* V^2*. The current is limited by the transport lens system, which must overcome the beam defocusing force due to space charge.*

Ion Induction Linac Design

A heavy ion I.L. driver for inertial confinement fusion is typically required to accelerate 300 μC of charge from an injection energy near 1 MeV to a final energy near 10 GeV. The requirements on the beam are to provide a total energy of about 3 MJ, an instantaneous beam power of more than 100 TW, and a beam power density of about 300 TW/cm^2 at the target. To reach these requirements the transverse and longitudinal emittances of the beam must both be kept small. In common with other accelerators, the I.L. is current limited at injection. In contrast to other accelerators, the beam current can be adjusted during acceleration by controlling the length of the bunch. In particular, it is possible and desirable to maintain the current near the maximum transportable level in the low and medium energy portions of the machine and in the final bunching lines leading to the target.

At the present state of technology, the modulators used in I.L.'s are closing switches which have a considerable dead time after a pulse. Also, an appreciable time interval is required to reset the induction cores efficiently. The consequence of these limitations is that the entire charge desired at the output must be accelerated as a single bunch. In an rf linac the average current stays constant even though the transportable current increases. A tree of linacs has frequently been suggested at the low energy end to funnel current from parallel linacs into eventually a single linac at higher energy to match the transport capabilities of an rf linac at high energies to the beam current. The process would be discontinued at currents of a few amperes because of the peak rf power requirements that such high beam current entails. An I.L. can handle beam currents in the kiloampere range without particular difficulty, and in fact only becomes efficient for currents above about a hundred amperes because of the large currents required to establish the induction field. The rf and I.L. schemes are shown in Fig. 1.

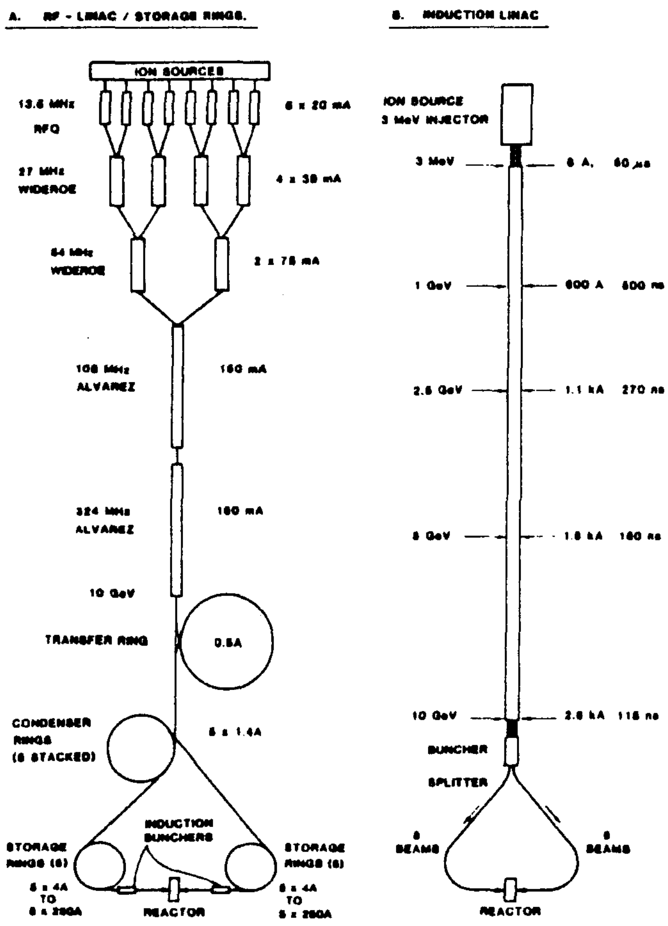


Fig. 1. Schematic of the proposéd r.f. and induction linac driver systems.

Bunch length control is an essential part of the ion induction linac. If the induction linac generates flat voltage pulses, as is commonly the goal for electron induction linacs, and a low intensity monoenergetic ion beam is injected into it, then during acceleration the bunch length will increase as β, or the square root of beam energy, the current will remain constant, and the exit energy will be constant. If, as a second possible scenario, a low intensity bunch is injected into a linac and then the accelerating fields are turned on with a constant average value, the bunch length will remain constant during acceleration, the current will increase as β, and at the exit of the machine the rear of the bunch will gain some additional energy. As a last example, if the low intensity bunch is given a linear momentum tilt, increasing from front to rear, the bunch will reach a longitudinal focus at some position downstream a time $t = L/\Delta v$ later. It should be emphasized that relatively small velocity differentials account for these three completley different types of bunch evolution.

Which particular bunching program is to be followed is largely determined by the type of transport system employed, the magnitudes of the attainable focusing fields, and economic tradeoffs. At very low energies, say, 1 - 20 MeV, available electrostatic lenses are stronger than available magnetic lenses and are therefore employed in the focusing of ion beams. Assuming that the maximum electric field strengths are utilized at the lowest energies, the preferred strategy is to use the same transverse lens geometry and field limit, and to increase the focusing element lengths in direct proportion to particle velocity. In this case the current scaling law with energy is as given in the second example, i.e., constant bunch length with energy.

At higher energies, say, 20 MeV, available magnetic lenses are stronger than electric ones, and the focusing system can be changed to magnetic, although economic considerations tend to delay the cross-over point to somewhat higher energies. After the cross-over, again assuming that the peak (magnetic) field is the limit, the allowable current can increase with the kinetic energy, eV, as $I \propto V^{5/6}$. The current increase will fall below the maximum limit with increasing energy because of economic tradeoffs.

Also, for economic reasons, it is advantageous to accelerate a cluster of beamlets in parallel rather than as one, bigger, beam. The primary motivation for this has been from the need to keep the beamlet radius small in the final focusing lenses to decrease aberrations. The second major motivation for accelerating multiple beamlets is the desire to avoid the dilution which would result from splitting a single beam emerging from the accelerator for ease of final transport and focusing, as in our earlier designs. Ideally, without dilutions, and with transport limited by peak field strengths, the emittance of each of n individual beamlets into which a beam with emittance, ε, is subdivided is $\varepsilon_n = \varepsilon/\sqrt{n}$ and the transportable current, I, increases as $n^{2/3}$. Realistically, making allowance for clearances around the beam and the space taken by the focusing lenses, the actual current gain is much smaller, and undoubtedly has a maximum for some n instead of increasing indefinitely. In our conceptual designs, subdivision has increased the current several fold over that of a single beam, and resulted in cost savings, with a broad optimum in the range of 4 - 16 beamlets for the bulk of the machine where superconducting magnetic lenses are used.

At the end of the accelerator the emphasis changes from increasing the beam energy, that is, volts, to increasing the beam current to achieve the desired high power at the pellet. This is accomplished by rapidly bunching the beam in a relatively short drift section between the accelerator and the fusion reactor. In previous designs, such as reported in the proceedings of the preceding conference of this series, the same conservative criteria were applied to the short final bunching lines as were used in the design of the accelerator, namely, stable steady state transport in a lattice using a 60° - 24° tune window based on analytic theory for a beam with a Kapchinskij-Vladimirskij distribution. At that time computational simulation results were just beginning to indicate that a greater tune depression and correspondingly higher current are acceptable. Recently, these simulations have been extended much further, to tune depressions of about 1°, essentially indicating that practically any current is transportable, provided that the beam aperture is made large enough. Until these matters are finally resolved by experiment nothing definitive can be said except that, as before, the peak field and necessarily small beam size in the final lenses require about 16 beams for focusability, and the accelerator will use a number of beams based on the economics, but with more current than previously.

Waveform Synthesis

The longitudinal field acting on a particle is composed of the externally applied field, the beam induced field resulting from the passage of the beam current through the impedance at the accelerating gaps, and the averaged space charge field of the beam in the geometries of the transport elements and the accelerating gaps (high frequency spatial and temporal oscillations are averaged out by the inertia of the heavy ions and by the transit time factors of the gaps). The fields caused by the beam have magnitudes which are of the order of 10% of the applied accelerating fields and durations comparable to the bunch length and the bunch rise and fall times for the induced and space charge fields respectively. For the beam parameters of interest, both the local spread of particle velocities and the speed of space charge waves are slow compared to the average bunch velocity, therefore relative particle motion is insignificant in the interval between accelerating gaps.

The waveforms desired at any location are synthesized by calculating the longitudinal kinematics of a bunch without space charge which would keep the transverse tune of a high current bunch within a prescribed tune window. The longitudinal high intensity corrections are then added to the prescribed low intensity waveforms in such a way that the total field acting on a particle is restored to its low-intensity value. The largest deviations from flat accelerating waveforms are a result of the desired bunch length control at the front of the machine and of the establishment of a momentum ramp near the exit of the machine for bunching. The next largest deviation from constant voltage is a "pusher" bump or ear which follows the trailing edge of the bunch and counteracts the space charge field at the rear of the bunch and acts in the sense of accelerating the trailing end. Because the end correction has a much more rapid time variation than the main accelerating pulse at any one location, it is desirable to use separate short pulse modules for this function. Because the bunch duration decreases from some 10 μs at injection to 100 ns at the exit, the short pulse modules at most locations are simply the full pulse modules taken from a location further upstream where the bunch duration has decreased appropriately. These short pulse modules also boost the trailing end of the full pulses which have a tendency to sag as the induction cores approach saturation. While it is possible to create a higher voltage ear at the end of the pulse generated by any induction module and pulse forming network (PFN) combination, this would necessitate the use of more sections of lower dispersion in the PFN. The current-induced corrections are small at the front end of the machine, because the beam current is of the order of 10 amps, compared to the core current of about 1000 amps; however, the beam current increases rapidly along the accelerator and can exceed the core current at the high energy end. Since the beam drives the core, PFN, and any compensation network in parallel, the effective impedance seen by the beam can be very much lower than the quantity $\Delta V/I_{beam}$.

To generate the desired waveforms, the plan is to use a very large number of a few types of accelerating modules, each powered by a relatively low voltage but inexpensive pulser with independent timing control, and to approximate the desired waveforms in staircase fashion by appropriately delaying the firing times of the modules. A 12 module induction unit of this type has been constructed and accelerated Cs ions [1]. While the idealized beam dynamics are calculated on the basis of smooth fields, the actual voltages are applied discontinuously, in the gaps, and have various errors as to timing and amplitude at any location. The tolerable errors based on a single particle approximation and without relative motion of the particles are very favorable, because truly systematic errors can be taken out at any location under the given assumptions, and random errors, for the more than 10^4 pulsers which are required result in an output error of < 1% of the error on the applied individual waveforms. The nonrelativistic motion of the ions complicates this favorable result even without space charge in that high spatial frequency errors would be averaged out by the motion of the particles, while the low frequency errors, such as tilts, would accumulate, therefore the form of the error voltage must be taken into account. Space charge is a further, possibly favorable complication for the longitudinal error problem, with the effect that errors are transformed into wavelike motion along the bunch which tends to average them out over the beam particles as well as probably heating up the ends of the bunch. All of these questions will be studied in greater detail after the overall transport and final focusing problems settle down.

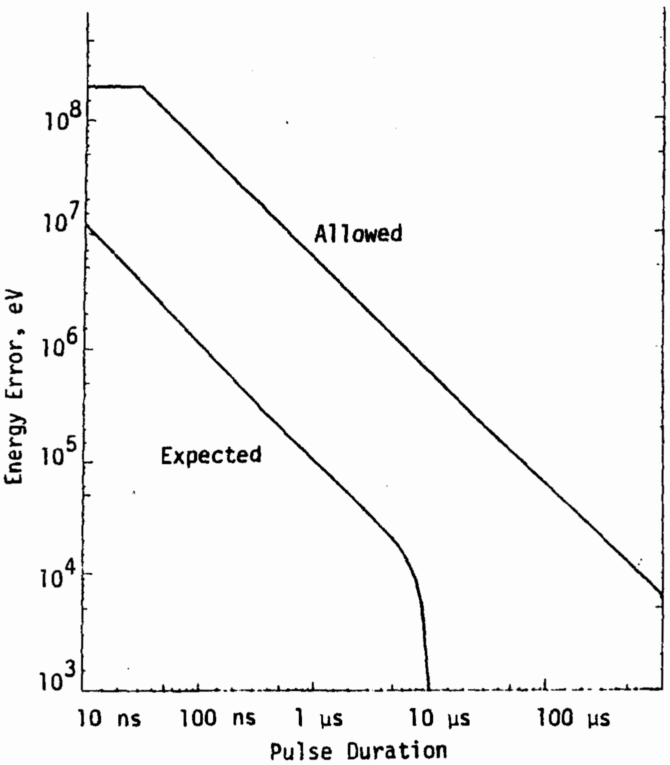


Fig. 2. Allowed and expected energy errors.

From the conservation of longitudinal phase space, $\Delta E\ \Delta t$ = constant, it is clear that acceleration errors should be relatively small when the bunch duration is long. For purposes of orientation, we choose an acceleration scenario where the desired voltage is composed of 25 kV steps, which is a reasonable level for the 10 μs pulse duration required by the transport limitations at low energy. Assuming a random voltage error amplitude of 1 kV per step, the effect on the energy of a low intensity bunch would be approximately as shown in Fig. 2, which also shows the maximum allowable energy error as a function of pulse duration based on the phase space requirements for final focusing, which at this time are a momentum spread of less than ±1% at the target for a 30 ns pulse. The 1 kV noise for this example is treated as occuring along the entire pulse. A real pulse, similar to the one produced by a prototype module, would have the noise generated mainly by the firing jitter of the module and therefore localized near the ends of the pulse, where the rate of change of voltage is greatest, i.e. $\Delta V = (dV/dt)\Delta t = (25\ kV/.5\ \mu s) \times (\pm.02\ \mu s) = \pm 1$ kV, based on measurements. For this pessimistic approximation, the longitudinal phase space grows from zero at injection to about 1/10 of the allowable limit of 6 eV-seconds in the long pulse portion of the machine, and does not increase substantially afterwards, where most of the energy is added to the beam. It should be noted that if the entire energy were gained in a long pulse configuration, then the waveform tolerance is $\Delta V/V$ = 4%. At the opposite extreme, the shortest pulses and highest voltages contemplated in our conceptual designs, 100 ns and 500 kV respectively, lead to an 80% waveform tolerance. Whereas the random error tolerance is very loose, the systematic error tolerance is very tight, but being systematic, these errors should be removable either at their source or downstream at a location shorter than that required for mixing of the errors either by particle or wave motion on the bunch. It may be fortunate that most of the initial bunch launching schemes into an induction linac require a low field start for bunch length and transverse control reasons, resulting in small steps at low energies.

In conclusion, the present driver designs are based on transverse focusing constraints and economic tradeoffs. The resulting longitudinal phase space growth, based on attainable tolerances, appears adequately small for the ICF application, but the detailed calculation of the expected longitudinal phase space would be premature until an optimum driver scenario has evolved and sufficiently many prototype modules have been developed to attain firm numbers for the expected magnitudes and types of waveform errors.

Acknowledgment

This work was supported by the Assistant Secretary for Defense Programs, Office of Inertial Fusion, Laser Fusion Division, U.S. Department of Energy, under Contract No. DE-AC03-76SF00098.

References

1. A. Faltens, M. Firth, D. Keefe, S. Rosenblum, IEEE Trans. on Nuclear Science, NS-30, 3669 (1983).